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Monitoring Concept for CO_2 Storage at the Ketzin Pilot Site, Germany – post-injection continuation towards transfer of liability

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Abstract

At the Ketzin pilot site the GFZ German Research Centre for Geosciences has developed an interdisciplinary monitoring concept for CO_2 storage, which incorporates different permanent and periodic measurements. The concept mainly bases on seismic, geoelectric, borehole and geochemical monitoring and focusses on the storage complex, the overburden, the surface and the wellbores. After the end of injection in August 2013, this concept is now continued and applied for post-injection monitoring to address long-term site performance to finally transfer liability to the competent authority. Experiences gained at the Ketzin site may be transferred to other CO_2 storages pilots and also industrial-sized projects.

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Keywords: *CO_2 storage, Ketzin pilot site, monitoring techniques, seismics, geoelectrics, borehole monitoring, transfer of liability.*

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1. Introduction

Between 2008 and 2013, the GFZ German Research Centre for Geosciences has injected more than 67 kt of CO_2 at its pilot site for geological storage of CO_2 in Ketzin/Havel, which is located 25 km west of Berlin. Most of the injected CO_2 had food grade quality (99.9% CO_2) and was delivered by trucks to the storage site. On-site the

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delivered CO_2 was temporarily stored in two tanks (50 metric tons each) before it was injected into porous sandstones of the Upper Triassic Stuttgart Formation at a depth between 630 and 650 m. To monitor the subsurface behaviour of the injected CO_2 and to ensure safe and reliable injection operation a multi-disciplinary monitoring concept has been developed and applied at the Ketzin site (Fig. 1). The monitoring concept comprises different geophysical, geochemical and operational methods and focusses on four major compartments, the storage complex, the overburden, the surface and the wellbores. Detailed descriptions of the monitoring concept are given, e.g., in [1], [2], [3], [4], [5], and [6].

The EU Directive of 2009 on geological CO_2 storage defines three minimum high-level criteria for satisfactory long-term site conformance and transfer of liability: i) observed behaviour of the injected CO_2 conforms to the modelled behaviour, ii) no detectable leakage, and iii) site is evolving towards a situation of long-term stability. To provide first-hand experiences and learnings on post-injection operation and closure procedure to other storage sites and projects, design and operation of the post-injection phase at the Ketzin site are guided by these three high level criteria although the Ketzin pilot site has been permitted and will be closed according to the German mining law and the regulations of the EU Directive will not directly apply. In this regard, the monitoring is continued in the final phase and new experiences on post-injection operations and closure procedures are gained. This contribution reviews main outcomes from post-injection monitoring at Ketzin and discusses these results in the context of a transfer of liability for Ketzin and other CO_2 storage sites.

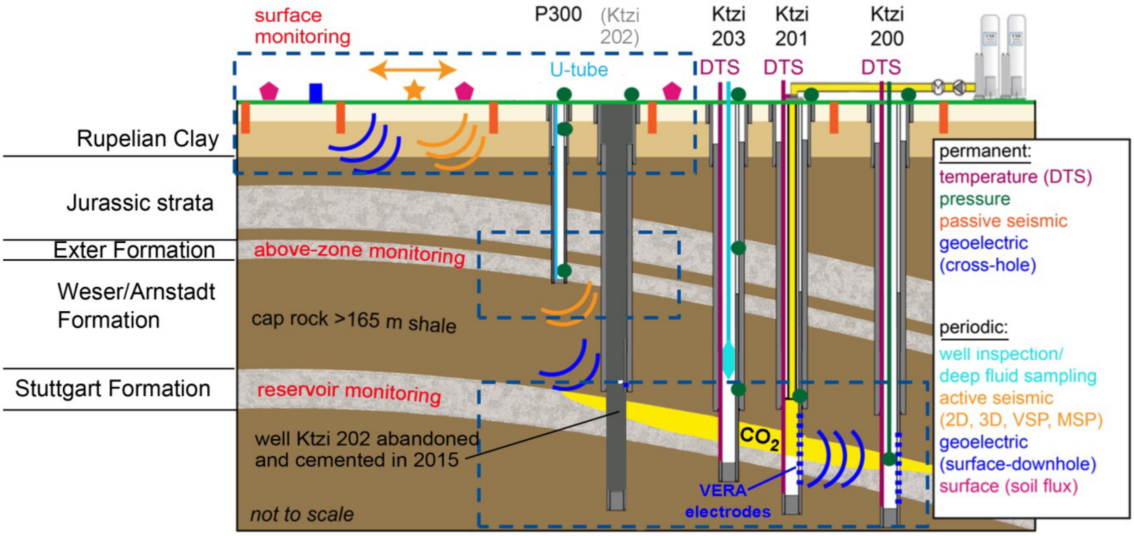

Figure 1: Schematic sketch of the Ketzin anticline and infrastructure built at the pilot site for injection and monitoring purposes. Four deep wells Ktzi 200, 201, 202 and 203 have been drilled to reservoir depths and which allow the monitoring of the storage complex. Shallow well P300 reaches the first aquifer above the cap rock and allows for an above-zone monitoring.

2. Geological setting, research infrastructure and general monitoring concept

The storage site is located near the town Ketzin/Havel in the federal state of Brandenburg (Germany) above the south-eastern flank of the so-called Roskow-Ketzin double anticline, which formed above a deep-seated salt pillow (Fig. 1). The storage reservoir consists of sandstone units of the Upper Triassic Stuttgart Formation at depths between 630 and 650 m [7]. The reservoir is sealed by a multi barrier system. The primary seal is > 165 m clay- and mudstones of the Weser and Arnstadt Formations, which are in turn overlain by a thick sequence of alternating permeable and impermeable layers of Upper Triassic and Jurassic age. Sandstone units of the Exter Formation directly above the primary seal serve for above-zone monitoring. The final seal is the Oligocene Rupelian Clay at the base of the Tertiary that, in northern Germany, typically separates salt water horizons below from freshwater horizons above. In principal, the geologic setting at the Ketzin site is representative for the entire North-German Basin and results gained here may be transferred to potential future German storage sites.

Four deep wells, Ktzi 200, 201, 202 and 203, have been drilled down to reservoir depth for injection (Ktzi 201) and observation (all wells) purposes (Fig. 1). Well Ktzi 202 has already been abandoned in two stages in 2013 and 2015 and is not available anymore for post-injection monitoring. The wells are equipped with different types of smart casing that allow for downhole pressure and temperature monitoring, distributed temperature sensing along the wells, and downhole geoelectric measurements with permanently installed electrodes of the vertical electrical resistivity array VERA [8], [9]. For above-zone monitoring the shallow well P300 has been drilled into the first aquifer of the Upper Triassic Exter Formation above the cap rock (Fig. 1). Well P300 is equipped with downhole pressure and temperature gauges and a U-tube system for deep fluid sampling [10]. Further monitoring infrastructure includes a permanently buried multi-component seismic array for continuous recording of passive seismic data, which consists of thirteen 50 m deep wells [11].

The multi-monitoring concept at the Ketzin pilot site targets the storage complex, the overburden, the surface and the wellbores. The behaviour and spread of the injected CO_2 within the storage complex is monitored by i) cross-hole, surface-downhole and surface-surface geoelectric methods, ii) 2D-, 3D-, VSP and MSP active seismic as well as passive seismic methods, and iii) pressure-temperature monitoring. Integrity and tightness of the cap rock is monitored by pressure-temperature measurements and deep fluid sampling in well P300 and the surface is monitored by CO_2 soil flux measurements and groundwater fluid sampling. Wellbore integrity is routinely monitored by standard methods like pulsed neutron gamma logging, magnetic induction defectoscopy, video inspection and P-T profiling. All methods are applied either on permanent or periodic basis. Except for above-zone monitoring through well P300, which was drilled in 2011, baseline measurements for all methods were performed prior to start of CO_2 injection. Geophysical and geological baseline information was integrated in a geological 3D-model for the Ketzin pilot site, which is regularly updated based on new monitoring data. By using this static model, numerical simulations based on a history matched dynamic model are used for prediction of site behaviour.

Injection of CO_2 started on June 30th, 2008, and ceased on August 29th, 2013. After injection of 67 kt CO_2 the site entered into the post-injection phase (Fig. 2). The injected CO_2 was predominantly food-grade with purity > 99.9%, only in May and June 2011 about 1.5 kt of captured CO_2 from the oxyfuel pilot plant "Schwarze Pumpe" with purity > 99.7% had been injected.

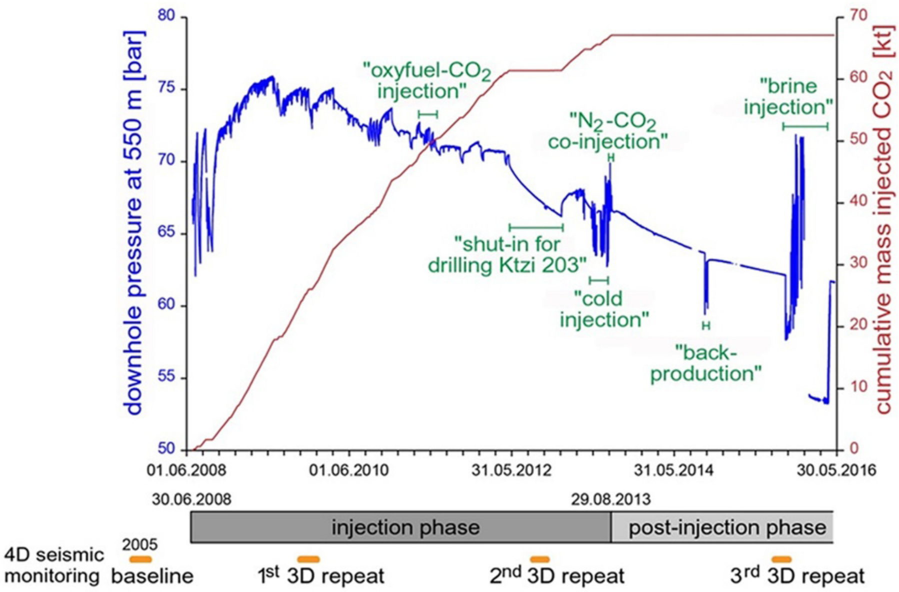

Figure 2: Injection history shown with respect to cumulative mass of injected CO_2 (red) and corresponding evolution of reservoir pressure (blue) as recorded by pressure sensor in injection well Ktzi 201 at 550 m depth. Timing and duration of different field experiments are shown in green. Timing of the three 3D seismic repeat measurements is shown below the chart. The second repeat was performed at ~ 61 kt CO_2 and may serve as "baseline" for the post-injection evolution of the CO_2 plume.

At the end of the injection phase, two field experiments on “cold injection” and “N_2-CO_2 co-injection” had been performed [12], [13]. During the post-injection phase two further field experiments on “CO_2 back-production” and “brine injection” were executed [14], [15]. Despite its application for normal site monitoring, the installed monitoring infrastructure was used to scientifically and operationally surveil and control the different field experiments. While reservoir pressure rose between 11 and 17 bars during active injection phase when compared to initial reservoir pressure of about 62 bar [5], it immediately started to decrease with end of injection, reaching about 64 bar already in May 2016 (~ 62 bar measured at pressure gauge at 550 m depth as shown in Fig. 2), and were smoothly approaching initial pressure conditions.

3. Storage complex monitoring by 4D time-lapse seismics

Time-lapse seismic surveying is the most commonly used periodic method for imaging, comparing and monitoring spread and behaviour of the CO_2-plume in the deep subsurface. At the Ketzin pilot site, a total of four 3D seismic surveys have been accomplished up to now (Fig. 2). The baseline was acquired in 2005 covering an area of approximately 14 km^2 [16]. During the injection phase, two 3D repeats were measured, the first repeat in 2009 after approximately 22 kt of injected CO_2 and the second repeat in 2012 after approximately 61 kt injected CO_2 [17], [18]. According to predictions by numerical simulations, the area covered by the first repeat was only 7 km^2 while that of the second repeat was 10 km^2. In 2015, about two years after end of injection a third 3D repeat was acquired covering an area of about 12 km^2 [19]. As the second repeat from 2012 was acquired only 0.5 years before the end of injection at a total mass of injected CO_2 only 6 kt below final cumulative mass of injected CO_2, it may serve as a “baseline” to study post-injection behaviour and stabilization of the CO_2 plume.

Figure 3 shows size and propagation of the CO_2 plume for the repeat surveys acquired in autumn 2009, 2012, and 2015 based on normalized amplitude differences between repeat and baseline, extracted at the top of the Stuttgart Formation [19]. From 2009 to 2012 a significant increase of the CO_2 plume footprint area can be detected from about 0.08 km^2 in 2009 to 0.15 km^2 in 2012 reflecting increase of injected mass of CO_2 from about 22 kt CO_2 in 2009 to about 61 kt CO_2 in 2012. Areal increase from 2009 to 2012 is roughly isotropic without preferred direction and does not provide any evidence for overall significant movement of the plume during these years. Compared to the 2012 repeat, the 2015 repeat indicates shrinkage of the CO_2 plume footprint area during the post-injection phase. Shrinkage is most prominent east and south-east of injection well Ktzi 201 while extend of CO_2 plume footprint is comparable between 2012 and 2015 repeats in other directions.

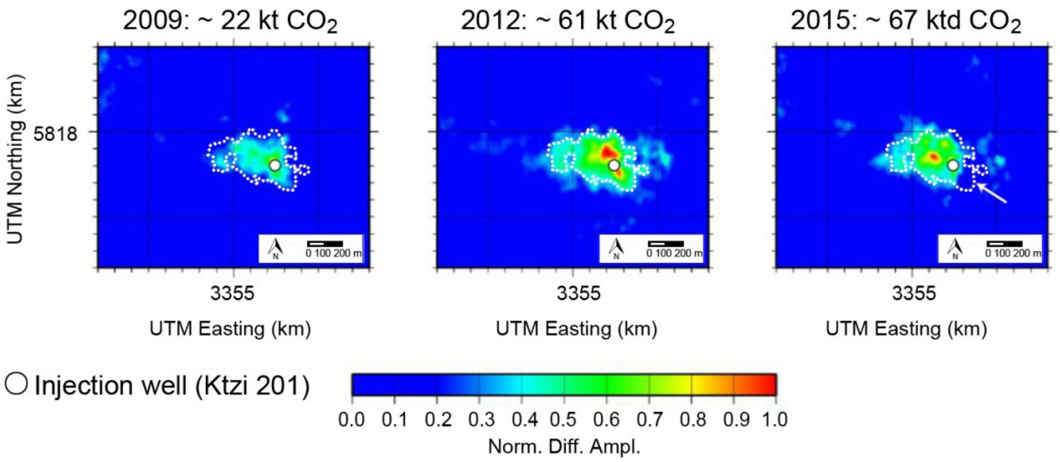

Figure 3: Difference amplitude maps at the top of the Stuttgart Formation, indicating the lateral extent of the CO_2 plume for the years 2009 (~22 kt CO_2 injected), 2012 (~61 kt CO_2 injected) and 2015 (~67 kt CO_2injected; from left to right). The eye-drawn stippled white lines indicate extension of the CO_2 plume as recorded by the 2012 repeat. The post-injection repeat in 2015 indicates predominant shrinkage of the CO_2 plume from ESE (white arrow) and a slight migration of maximum CO_2 signature from the injection well towards WNW.

Besides overall area of CO_2 plume footprint also the areal extend of maximum normalized amplitude differences decreased from 2012 to 2015 repeat. The location of this area of maximum normalized amplitude differences is also suggestive of slight movement towards the north-west. Two processes may be responsible for the observed shrinkage of the CO_2 plume footprint area: (1) Dissolution of a significant amount of CO_2 into the formation brine, which is then no longer detectable for seismic measurements, and (2) overall thinning of the free CO_2 plume. In a conformance study for the Ketzin site based on the 2009 and 2012 repeats, [20] showed that best conformance between seismic monitoring results and numerical simulations is achieved for thickness thresholds above 6.5 m and normalized amplitude thresholds from at least 0.2. This data indicate that thinning of the CO_2 plume notably below 6.5 m may not be resolvable by seismic methods at the Ketzin site and may therefore result in too small CO_2 footprint area in seismic imaging.

4. Above-zone monitoring via well P300

The shallow well P300 was drilled in 2011 to a depth of 446 m into the first aquifer above the cap rock ("indicator horizon"). It is equipped with three pressure gauges at 418 m and 21 m depth and at the wellhead allowing a continuous and detailed above-zone pressure monitoring and hence the identification of pressure changes that may reflect a hydraulic connection between reservoir and indicator horizon or even leakage of displaced brine or CO_2. Pressure measured at 21 m depth is extrapolated to downhole pressure at 418 m depth by adding the in-well fluid weight column to allow check of internal consistency of measured pressure data. Temperature is monitored at 418 m and at the wellhead [10]. The geochemical monitoring is realized by regular fluid sampling at 415 m depth with the permanently installed U-tube system (Fig. 4) [10].

Since the start of recording in September 2011, the downhole pressure in well P300 shows only very minor changes (Fig. 4). Pressure measured at 418 m depth fluctuates between 41.05 and 41.18 bars and suggests increasing pressure until summer 2014 and almost constant pressure conditions afterwards. The downhole pressure calculated based on the data recorded by the pressure gauge at 21 m, on the other hand, shows a slight but continuous increase from 41.07 to 41.25 bars over the entire recording period. The reason for the observed divergence between measured and calculated downhole pressure after summer 2014 is not fully clear but may reflect operational problems with the pressure gauge at 418 m depth. In any case, the pressure of the indicator horizon appears to be fully decoupled from the underlying reservoir. During the recording period the reservoir pressure as measured in injection well Ktzi 201 at 550 m depth decreased from about 71 bars in September 2011 to almost 62 bars in April 2016. Furthermore, different field experiments are characterized by notable, distinct variations of several bars reservoir pressure (Fig. 4). None of these signals can be seen in the indicator horizon. This indicates that there exists no leakage of displaced brine or CO_2 between the reservoir and indicator horizon.

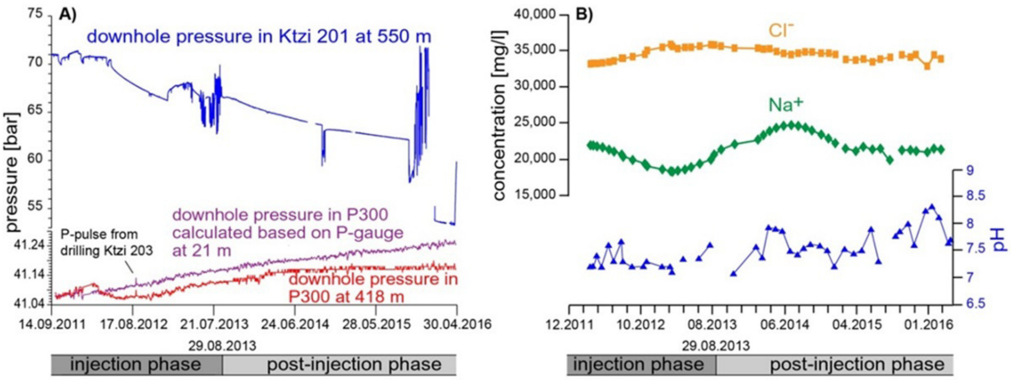

Figure 4: A) Comparison between pressure in the reservoir as recorded by the downhole sensor at 550 m depth in well Ktzi 201 (blue) and in the above-zone Exter Formation as recorded by the downhole sensor at 418 m depth in well P300 (red) and calculated based on pressure gauge at 21 m depth (purple). Note different y-axis scaling for Ktzi 201 and P300 pressure data. B) Chemical characteristics (Cl^-, Na^+ and pH) of downhole fluid samples from the above-zone Exter Formation as sampled via the permanently installed U-tube system in well P300.

Like the pressure data, the fluid samples from well P300 do not provide any evidence for infiltration by external fluids from the underlying storage complex (Fig. 4). Chloride concentrations of fluid samples from well P300 show only small variations between about 33 and 36 g/l without any temporal correlation to the reservoir pressure. Sodium concentrations display a slightly higher variability between about 18 and 25 g/l but likewise lack any correlation with reservoir pressure. The recorded Cl^- and Na^+ concentrations are about five times lower than the salinity of the initial reservoir brine of the Stuttgart Formation and any infiltration of vertically displaced brine from the CO_2 storage complex should therefore result in a time dependent increase in salinity of the fluid samples from P300. Like the major element concentrations also the measured pH of the fluid samples is almost constant ranging between 7 and 8.4 with slightly higher values since summer 2014. However, upward migration and infiltration of leaking CO_2 should result in a decrease of pH in the indicator horizon and the measured data therefore provide no hints to any CO_2 leakage and infiltration.

5. Surface monitoring

The final seal of the multi-barrier system at Ketzin is the Oligocene Rupelian Clay at the base of the Tertiary and surface monitoring by natural CO_2 soil flux measurements and sampling and analysis of soil gas therefore intends to monitor overall integrity of this multi-barrier system. The CO_2 soil flux determination is performed periodically at 20 stations covering an area of about 2 x 2 km^2 and by this a large portion of the Ketzin part of the Roskow-Ketzin double anticline [21] plus 8 automated stations directly on site. Monitoring of CO_2 soil flux already started in January 2005, 3.5 years before the start of injection, and now provides an exceptional 11.5 years long time series of pre-injection, injection and post-injection data (Fig. 5). The data clearly indicate a strong positive, seasonal correlation between measured CO_2 soil flux and soil temperature reflecting the dependency of CO_2 soil fluxes on soil temperature and biological activities with maximum values in summer and minimum values in winter. The data presented in Figure 5 are mean values for the entire monitored area and slight variations in yearly maxima largely reflect yearly variations in contribution of individual sampling locations due to changes in agricultural use; in addition, since 2012 frequency of sampling has been increased and short-term maxima in CO_2 soil fluxes may have been smeared out in the former years by averaging over a larger time interval.

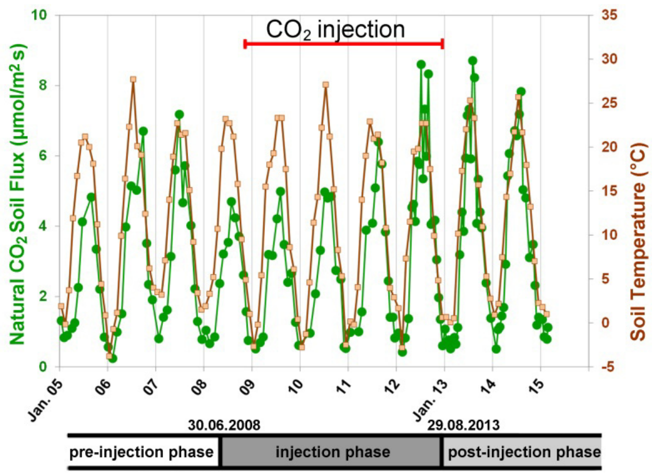

Figure 5: Measurements of CO_2 soil flux (green) and soil temperature (brown) between 2005 and 2016, spanning 3.5 years of pre-injection baseline, five years of injection phase and 2.5 years of post-injection monitoring. Data are averaged over all stations.

However, with respect to leakage monitoring the minima in the wintertime are more important than yearly maxima as leaking CO_2 would contribute to measured CO_2 soil fluxes independently upon season and soil temperature. The winter times minima show no changes throughout the monitored period and therefore no indication for any leakage. This interpretation is supported by additional, exemplary sampling and analysis of soil gas in 2015.

CO_2 concentrations and N_2/O_2 ratios in soil gas samples recovered during March 2015 resemble background atmosphere values whereas samples recovered during autumn 2015 show a positive almost linear correlation between CO_2 concentrations and N_2/O_2 ratios, indicating biogenic CO_2 production via oxygen consumption and passive enrichment of N_2.

6. Borehole monitoring

Wellbore integrity is one of the most crucial issues for safe CO_2 storage. During the injection phase integrity of cement and casing material is important to ensure sustainable injection process whereas knowledge on well integrity status is essential for any proper and safe long-term abandonment of CO_2 wells especially during the closure phase. Wellbore integrity is monitored at Ketzin via repeated pulsed neutron gamma (PNG) logging, magnetic induction defectoscopy (MID) and video inspection. While PNG logging provides information on potential changes in pore fluid composition in the very near wellbore area and by this may be indicative for upward CO_2 infiltration of the cement, MID and video inspection provide information on casing thickness and therefore potential corrosion as well as visual images of corrosion effects. The different well inspection techniques have been applied since start of injection on a biannual to annual basis. PNG logging did not provide any evidence for CO_2 infiltration into the casing cement or even leakage to higher strata through the casings and data from MID show casing thicknesses within reported production tolerance for the used casing materials. Well integrity measurements therefore show no well integrity issues. In 2013, well Ktzi 202 was partly cemented and abandoned in the reservoir section up to a depth of 521 m after general integrity of the casing and casing cement had been proven. The integrity of this stage 1 cementation had been monitored by a gas membrane sensor within well Ktzi 202 that allowed probing of the in-well gas composition to detect any potential CO_2. After integrity of Stage 2 cementation had been proven, well Ktzi 202 was finally cemented and abandoned in 2015. Integrity monitoring of the other wells will be continued until final abandonment of all wells by summer 2017.

7. Conclusions

The benefit of the applied monitoring concept, which has been carefully designed and tested at the Ketzin pilot site for more than a decade, was successfully demonstrated in the past and represents one of the most important results affecting all project phases and field experiments that were carried out at the site. Generally, monitoring plays a vital role not only for gaining scientific results but also in terms of safety of CO_2 storage. Admittedly, the concept in a strict sense has been developed for onshore CO_2 storages with pilot character. Storages on industrial scale as well as offshore storages most likely need to set other priorities which in turn are also strongly dependent on the specific geological situation. However, the monitoring concept of Ketzin, which comprise different reliable and tested monitoring methods in its “tool box”, can be applied also for other CO_2 storages by putting together the necessary modules in a meaningful and economically acceptable manner.

Besides the scientific questions and those related to the injection operation, the monitoring program focusses on safety requirements during all phases of a CO_2 Storage Life Cycle. Although post-injection monitoring is on-going, some general statements on the minimum high-level criteria for satisfactory long-term site conformance and transfer of liability as set out in the EU Directive, i.e. i) observed behaviour of the injected CO_2 conforms to the modelled behaviour, ii) no detectable leakage, and iii) site is evolving towards a situation of long-term stability, can already be drawn. ad i) Despite some minor discrepancies between the observed and modelled behaviour of the injected CO_2 there is general overall agreement between particularly 4D seismic results and dynamic reservoir simulations. ad ii) The combined above-zone and surface monitoring data do not provide authoritative indication that leakage and concomitant upward migration of CO_2 or displaced formation brine has occurred. ad iii) The 3rd post injection 3D seismic repeat indicates a more or less stagnant CO_2 plume that either starts to thin out or to dissolve in the reservoir formation brine; a notable migration of the CO_2 plume away from the injection site is not supported by the monitoring data. The recorded pressure data indicate return to initial formation pressure and by this also supports evolution towards long-term stability of the storage complex.

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